

## Z-Pinch ICF Target Symmetry: Input to Snowmass Symmetry Subgroup

R. A. Vesey, M. E. Cuneo, G. R. Bennett, D. L. Hanson, J. L. Porter  
*Sandia National Laboratories, Albuquerque, New Mexico 87185*

### A. Double-Ended Z-Pinch Driven Hohlraum

#### 1. What are pointing requirements? Specify allowed variations in power balance and pointing. Discuss both random and correlated fluctuations.

A key symmetry issue for the double-ended hohlraum configuration<sup>1,2</sup> shown in Figure 1 is the degree to which top-bottom pinch power imbalance translates to radiation asymmetry and perturbation of the capsule implosion. Pinch power imbalance can take the form of a simple mistiming of identical pinch power pulses (the pinch powers peak at different times) or a simple imbalance in the power output (pulses have the same timing but different amplitudes), but in general will be some combination of the two phenomena.

Spatial averaging alone in a hohlraum does not readily smooth out the lowest-order Legendre mode,  $P_1$ . For the specific case of double-ended z-pinch driven hohlraums, we have used a time-dependent viewfactor code to model mistimed and/or imbalanced top-bottom z-pinches and the resulting capsule  $P_1$ ,  $P_3$ ,  $P_5$ ,  $P_7$ , etc. Figure 2 shows the dependence of the time-integrated  $P_1$  coefficient at the capsule on pinch power imbalance for perfectly timed top and bottom pinches, for the case of an X-1 class machine at peak powers of 1200 TW/side with gold-gadolinium hohlraum walls. For this calculation, the pinch power imbalance is assumed to apply throughout the entire radiation pulse implying a total energy imbalance. A pinch power imbalance of 5% leads to time-integrated  $P_1$  coefficients between -0.7% and -1.7% depending on the level of pinch mistiming, with the higher-order odd modes related to  $P_1$  by:  $P_3 = -0.15 P_1$ ,  $P_5 = 0.021 P_1$ ,  $P_7 = -0.0024 P_1$ .

Variations in z-pinch output intensity as a function of position on the z-pinch emitting surface may occur as a result of azimuthal perturbations, electrode effects, or magneto-Rayleigh-Taylor instability. Due to the isolation of the capsule from the z-pinches in this concept, capsule symmetry is relatively insensitive to the spatial distribution of the pinch output. For example, 3D viewfactor simulations indicate that a hypothetical purely azimuthal  $m=2$  variation of  $\pm 50\%$  in the pinch output intensity, correlated between top and bottom pinches (worst case), results in only a 2.8% max-to-min flux asymmetry at the capsule.



**2. What are techniques of symmetry control in the target? How have they been validated? What convergence ratio has been demonstrated? What are the challenges in symmetry control for the various target designs?**

The main result of the simulations and experiments to date is that by properly choosing the geometry of the secondary hohlraum (the hohlraum containing the capsule), the level of radiation asymmetry at the capsule can be minimized. This may be accomplished by simply varying the radius and length of a cylindrical secondary hohlraum, by also varying the diameter of the on-axis shine shield at each entrance to the secondary, and/or by allowing a non-cylindrical secondary hohlraum shape to fine tune the symmetry.

To illustrate this point, Figure 3 shows the time-integrated maximum-to-minimum radiation asymmetry<sup>3</sup> as a function of secondary hohlraum radius and length, for fixed primary hohlraum geometry ( $R_{\text{prim}}=12$  mm,  $L_{\text{prim}} = 10$  mm) and fixed shine shield geometry ( $R_{\text{shld}}=4.0$  mm). This 2D viewfactor calculation used pinch pulse shapes containing a 60 TW foot pulse and 1200 TW peak power per side, gold-gadolinium albedo results, and a 2.5-mm radius capsule. The best case in this parameter space has a max-to-min fluence asymmetry of 0.52% for a secondary hohlraum radius and length of 10.5 mm and 18 mm, respectively. A 2D viewfactor symmetry optimization code has been used to seek hohlraum configurations that minimize the even Legendre modes 2 through 8 at the capsule. This was accomplished simply by varying the radius and length of a cylindrical secondary hohlraum, and the radius of the on-axis shine shield. The optimum configuration gave a secondary hohlraum radius of 10.4 mm, length of 17.6 mm, and on-axis shine shield radius of 4.0 mm. Legendre modes 2 through 8 all had time-integrated values less than 0.2%. Given the objective of minimizing the time-integrated Legendre modes, the optimization procedure has settled on a configuration for which the dominant modes,  $P_2$  and  $P_4$ , swing through zero near the time of peak capsule drive as the secondary hohlraum albedo rapidly rises. 3D viewfactor modeling of this configuration at peak pinch confirms the overall flux asymmetry levels found in 2D, and indicates that the spoke array at each entrance to the secondary hohlraum imprints less than 0.3% azimuthal max-to-min flux variations on the capsule. 2D LASNEX capsule simulations using the predicted time-dependent polar angle variations in the



incident radiation flux as a boundary condition gave ignition and full yield (400 MJ), despite a slightly perturbed imploded fuel configuration. Quasi-integrated LASNEX hohlraum and capsule simulations are currently being refined for this configuration.

Foam ball burnthrough experiments<sup>4</sup> in both single-pinch and double-pinch hohlraum configurations have been used to validate geometric symmetry control techniques and the various modeling techniques. The purpose of these experiments, in which the foam ball is backlit by the secondary hohlraum wall emission, was to demonstrate symmetry control first in highly asymmetric single-pinch configurations, followed by experiments in more symmetric double-pinch hohlraums. A transonic radiation wave is produced by the hohlraum radiation in 4.3-5.0 mm diameter 46-56 mg/cc foam spheres, and the superposition of the foam self-emission and the transmitted hohlraum wall backlighter photons forms a well-defined edge. The motion of this edge as a function of time acts as a drive diagnostic, and the distortion of the edge radius versus polar angle is sensitive to radiation asymmetry. The single-pinch experiments show reasonable agreement in the time-dependent foam ball burnthrough as a function of polar angle when compared with 2D quasi-integrated radiation-hydrodynamics simulations. This includes cases in which the foam ball drive was designed (using 2D viewfactor and LASNEX simulations) to be closer to equator-hot than the more typical bottom pole-hot drive. Double-pinch experimental results are more limited but demonstrated asymmetry levels at or below the measurement sensitivity for the self-backlit technique (~15% max-to-min).

Capsule implosion experiments on the Z machine using the Z-Beamlet Laser (ZBL) to generate backlighting x-rays<sup>5</sup> have recently begun to validate geometric symmetry control at the 2-5% level. Recent shots mapped the implosion trajectory of a 2-mm diameter, 60- $\mu$ m CH shell, driven at peak temperatures of 65-75 eV, over convergence ratios of 2 to 10. A number of experimental improvements have allowed high quality data to be obtained: (a) the use of a mechanically-isolated wire array gave shot-to-shot drive temperature reproducibility better than the  $\pm 5\%$  instrumental error, (b) continued improvement in the backlighter laser spot size (currently 125  $\mu$ m, 50  $\mu$ m feasible), (c) obtaining adequate backlighting fluence at 4.75-6.7 keV, and (d) the use of burnthrough foils on all capsule viewing apertures to inhibit the flow of high-Z plasma into the line of sight. By varying the length of the secondary hohlraum and observing the resulting backlit limb distortion at a convergence ratio of 4-5, a



systematic trend from equator-hot ( $-P_2$ ) to pole-hot ( $+P_2$ ) drive with increasing secondary length is observed, in qualitative agreement with simulations. Quantitative comparisons with simulations for these very recent (and preliminary) data are underway.

Challenges in symmetry control for this configuration include:

(a) Demonstration of adequate  $P_1$  control, diagnosed with central targets, that implies adequate top-bottom pinch power balance and simultaneity,

(b) Scaling of radial spoke electrode radiation transmission (65-71% inferred in Z experiments) to high-yield systems with higher-mass z-pinch plasmas.

(c) Quantitative understanding of effects such as time- and radially-dependent spoke electrode transmission, pinch plasma trajectory details, and output of nested wire arrays or internal pulse-shaping targets that influence capsule symmetry at the 1% level.

### **3. Do we need innovations to meet the needs of the various drivers? What symmetry control is required to implode capsules for fast ignition?**

Rudimentary pulse shaping has been demonstrated through the use of nested wire arrays on Z, but more programmed and precise pulse shaping is a developmental issue, and the effect of the pulse-shaping scheme (nested arrays, internal converter targets, etc.) on capsule symmetry must be assessed. From the standpoint of symmetry control for a given z-pinch output pulse, the double-pinch concept relies on fairly well established physics of x-ray interactions with high-Z hohlraum walls at the 200-250 eV level. Mixed composition gold-gadolinium hohlraum walls are part of the initial high-yield design to increase the wall albedo<sup>6</sup>, increasing hohlraum efficiency and capsule symmetry.

Studies of fast ignitor applications for the z-pinch driven hohlraum are just beginning. From the standpoint of radiation symmetry, a simulated single-pinch configuration can provide adequate time-integrated symmetry to implode a hemispherical capsule (a 90° cone-focused capsule implosion) in a secondary hohlraum to near-1D peak density, but the interaction of the capsule with the glide plane on which it is mounted has not been adequately modeled yet. A cone-mounted capsule in the double-ended hohlraum configuration could also be envisioned, but high-yield fast ignition schemes for this concept have not been explored in detail.



**4. How does driver to ablator coupling efficiency depend on the quality of symmetry control? (That is as a function of case to capsule ratio for indirect direct and capsule overfilling for direct drive).**

As an indirect drive scheme, the double-ended z-pinch driven hohlraum trades off driver-to-ablator efficiency against symmetry; better capsule symmetry is gained with larger volume hohlraums at the expense of increased wall energy losses. For configurations plotted in Figure 3 which have time-integrated max-to-min asymmetry of 2% or less, hohlraum efficiencies range from 5.6% to 6.7% depending on geometric details. The cases with >6.6% efficiency all have secondary hohlraum radii of  $R_{\text{sec}}=7.75\text{-}8.25$  mm and lengths of  $L_{\text{sec}}=12\text{-}13$  mm, significantly smaller than the minimum asymmetry case with  $R_{\text{sec}}=10.5$  mm,  $L_{\text{sec}}=18$  mm and 0.52% asymmetry quoted in Section 2 which had a hohlraum efficiency of 6.1%. Thus a 10% increase in the hohlraum efficiency (equivalent to an increase in capsule absorbed energy from 1.13 to 1.22 MJ in this case) translates to a factor of 4 increase in time-integrated asymmetry for the cases shown in this example. Hohlraum efficiency concerns are somewhat reduced by the high demonstrated wall-plug-to-x-ray efficiency for z-pinchs (10-15%) and low capital cost per radiated Joule ( $\$50\text{-}100 / \text{J}$ )<sup>2</sup>.

**5. How does symmetry control depend on driver characteristics (frequency, particle species, energy or spot size)?**

The driver in this concept is the simultaneous implosion of two z-pinchs in primary hohlraums above and below the secondary hohlraum containing the capsule. From the symmetry point of view, as stated above, this configuration generally succeeds in isolating the capsule from details of the z-pinch behavior. Design choices of the materials and initial configuration of the wire array(s), nested pulse-shaping layers, etc., and the accelerator parameters (i.e. voltage pulse delivered to the z-pinch load) are typically driven by the desired z-pinch output energy and pulse shape, rather than by symmetry concerns.

**6. What is the effect of electron transport and magnetic field generation on symmetry control for both direct drive and indirect drive?**

Electron effects on symmetry in z-pinch driven hohlraums have not been studied. High-energy electron generation may occur in the load region of z-pinch systems due to instabilities in the stagnated pinch plasma. X-ray emission observed on time-integrated images suggests electron beams formed on or near the axis are impacting the anode hardware, producing high-energy photons. However, the timing, spectrum, and energy content of these suprathermal electrons are highly uncertain. If axially-directed electron beams prove to be problematic, a double-pinch accelerator may be designed such that the cathodes, rather than the anodes, face the capsule.

Magnetic fields are of course necessarily present in z-pinch driven hohlraums. However, in this concept an array of radial spokes at each entrance to the secondary hohlraum is intended to isolate the capsule from the z-pinch plasma and its associated magnetic fields contained in the primary hohlraums. The several millimeter standoff of the capsule from the radial spoke arrays should also help with this isolation. If necessary, low-Z tamper foils or foams at each entrance can further inhibit advection of z-pinch plasma and any associated magnetic fields to the secondary hohlraum, with a small decrease in coupling efficiency. The interaction of the z-pinch plasma with the radial spokes is a 3D radiation-MHD problem and difficult to model. Limited experiments on Z that isolate the effect of spoke electrodes have demonstrated that z-pinch implosions in which one electrode is a radial spoke array produce 11% lower peak radiated power and 10% lower radiated energy than z-pinch implosions with two solid electrodes, with no appreciable difference in pulse shape, but these differences are well within the experimental error<sup>2</sup>. From the standpoint of albedo, magnetic field tamping effects on wall blowoff have typically not been included in the calculations but because wall energy loss scales with  $\rho^{-0.12}$  wall albedo may only be slightly increased in the primary hohlraums<sup>1</sup>.

**7. What experimental/theoretical program needs to be pursued? What part of this program is a specific IFE need? What experiments can be done on existing facilities? On IRE's? On NIF?**



Much of the necessary experimental validation of this concept is already underway as part of the Campaign 10 high yield assessment. The Z machine at Sandia National Laboratories is the premier facility to perform source development, hohlraum coupling, and integrated target symmetry experiments for the double-ended z-pinch driven hohlraum. The current proposed plan devotes 40% of Z shots to ICF experiments, with 2/3 of those shots for the double-pinch concept and 1/3 for the dynamic hohlraum. At the current shot rate on Z, this corresponds to 54 shots/year for the concept, to explore drive symmetry and capsule implosions (55%), ICF pulse shaping (20%), fast ignitor fuel assembly (15%), and double-pinch optimization (10%). This rate would continue through FY04, would decrease in FY05 as the upgrade to Z known as ZR proceeds, and would either resume the 54 shots/year pace or increase to 106 shots/year for double-shift operation of ZR. ZR will double the stored energy of the Z accelerator and should enable z-pinch x-ray sources with outputs of 2-2.8 MJ for ICF experiments in the double-ended hohlraum configuration. (For single-pinch experiments, this is only a factor of 3 to 4 below the high-yield design, which calls for 8 MJ output from each of the two pinches.) This will allow scaling studies of z-pinch performance, primary-to-secondary hohlraum coupling, and anode-cathode feed gap closure, which primarily affect energetics but need to be understood to optimize symmetry. ZR will also allow capsule implosion experiments with peak drive temperatures of 90-100 eV depending on hohlraum and power feed configuration. Experiments will continue to study capsule implosion symmetry via backlighting. Large diameter (4-5 mm) targets designed for high sensitivity as a symmetry diagnostic have been fabricated and await testing on Z: thin (15-30  $\mu\text{m}$ ) Ge-doped plastic shells for limb distortion and low-density (20-40  $\text{mg}/\text{cm}^3$ )  $\text{SiO}_2$  foam spheres for imaging of the ablatively driven shock. At the asymmetry levels expected, the response of a symmetry target at the center of the secondary hohlraum will provide the most precise measurement of pinch power imbalance, a key concern for double-pinch configurations. In addition, the development of neutron producing capsules and a low-background neutron detector on Z and ZR will enable a new class of experiments to diagnose drive, pr, burn temperature, and convergence ratio. At the end of FY07, the combined efforts on Z and ZR will have provided 150-200 shots for symmetry and capsule implosions, 75-100 shots for pulse shaping, 40-60 shots for fast ignitor fuel assembly, 30-50 shots for further source optimization, and 40-50 shots for scaling issues. Beyond ZR, a single-shot high-yield z-pinch



facility (typically called X-1) is needed to validate the scaling of double-sided pulsed power operation, z-pinch performance and optimization, hohlraum coupling, pulse-shaping, preheat, capsule symmetry, and of course high-yield capsule ignition and burn demonstration. For the double-ended z-pinch hohlraum this implies an accelerator capable of driving two 62 MA pinches, a total pinch x-ray output of 16 MJ (properly pulse-shaped), cryogenic capsules, and a radiological facility to handle fusion yields of 200-1000 MJ.

Theoretical capsule design and optimization for this concept can be further refined, as computational tools improve and experimental validation proceeds. This work would seek an "optimum" solution for the z-pinch load to produce the desired x-ray pulse shape, hohlraum configuration, and a capsule design sufficiently robust to symmetry perturbations. Most of this work is sufficiently addressed by 2D radiation-hydrodynamics and radiation-MHD codes. Theoretical and experimental understanding of the "1%" symmetry issues such as radial spoke / z-pinch interaction, pinch plasma trajectory and density distribution details, and the performance of nested wire arrays and/or pulse shaping targets will increase confidence that adequate symmetry can be predictably achieved. 3D radiation-MHD simulations will best address these issues as the codes become available.

From the standpoint of symmetry, issues addressed on Z, ZR, and follow-on facilities intermediate to X-1 are relevant but not specific to IFE. Experiments on NIF that address the performance of cocktail hohlraum walls (i.e. gold-gadolinium or more exotic mixtures) at radiation temperatures of 200-250 eV are directly relevant to this concept. NIF capsule implosion and ignition experiments are relevant to this concept because: (a) similar computational tools are being used to assess NIF and high-yield capsule sensitivity, and (b) scaling of capsule performance and robustness with increasing absorbed energy is relevant to high-yield capsules which are designed to absorb 1-2 MJ.

## References

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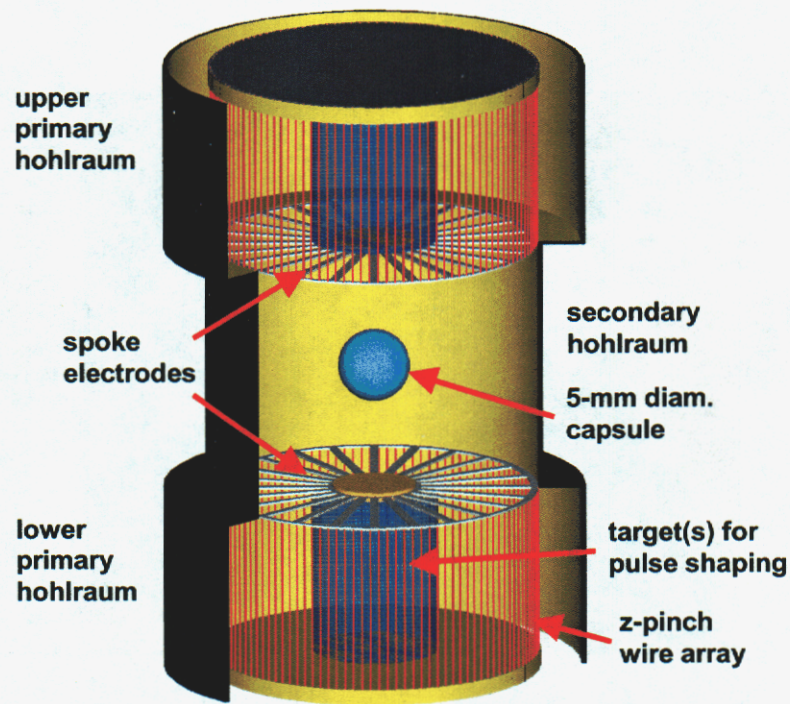


Figure 1. Schematic of double-ended z-pinch driven hohlraum high-yield concept.

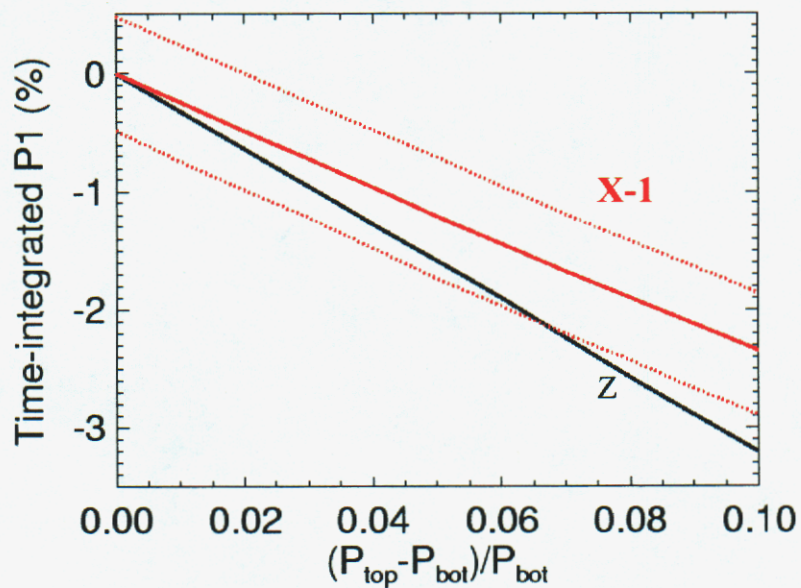


Figure 2. Time-integrated capsule  $P_1$  coefficient vs. top-bottom pinch power imbalance for X-1 (red) and Z (black). Solid lines are for the case of synchronized pinches. The dotted red lines indicate the  $P_1$  dependence for X-1 conditions with  $\pm 1$  ns mistiming of the top and bottom pinch power pulses.



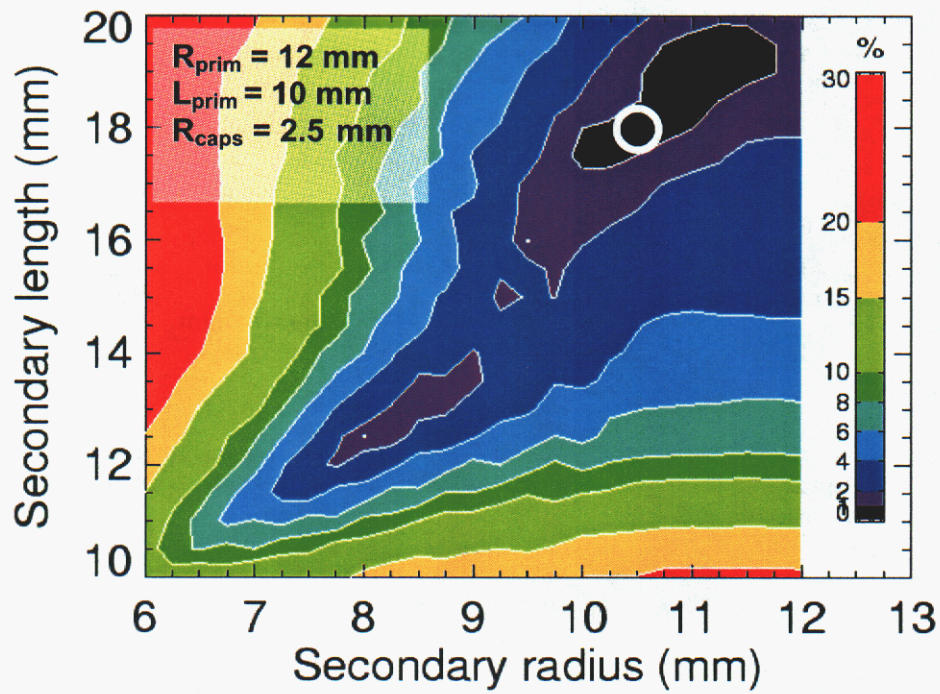


Figure 3. Time-integrated max-to-min fluence asymmetry contours as a function of secondary hohlraum radius and length. Example configuration within white circle has  $R_{\text{sec}}=10.5 \text{ mm}$ ,  $L_{\text{sec}}=18 \text{ mm}$ , and fluence asymmetry of 0.52%.